Chapter 5: Introduction of Cryomodule

Typical operating temperature of SRF cavities is 1.8 K~4.5 K

Helium circuit:
SRF cavities are immersed in liquid helium (helium vessel)
Helium supply and return lines are connected to helium vessel
Helium vessel can be pumped down to get lower temperature

Thermal design:
Minimize thermal loss
Typically uses multi-layer insulation and intermediate temperature boundary in a vacuum chamber

Power coupler: Couples RF power to a cavity

Mechanical tuner
Keeps a cavity on resonance or within a certain range of detuning

HOM coupler: Couples HOMs → damp and extract HOM

Magnetic shielding: Reduces ambient magnetic field
Keep cold efficiently

One of the major concerns in cryomodules. Large scale refrigeration plant is also one of major challenges for large scale machines.

Need a very careful consideration in thermal and safety points of view.
  thermal: minimize thermal loss or optimize operating condition
  safety: cryogenic incident (machine protection, personnel protection)

Insulation: reduce thermal heat transfer
  convection: vacuum chamber
  conduction: penetrations, supporting structures
  thermal radiation: Multilayer insulation (MLI), thermal shield
Heat Transfer

- Convection
- Conduction
- Radiation
Conduction heat transfer

When a temperature gradient exists in a body or between objects that are in physical contact, there's an energy transfer from the high temperature region to the low temperature region.

The heat transfer rate is proportional to area, temperature gradient

\[ q = -kA \frac{\partial T}{\partial x} \text{ [W]} \]

where \( A \): area for conduction

\( k \): proportional constant called thermal conductivity (material property) function of a temperature

\[ \frac{\partial T}{\partial x} \]: temperature gradient

Ex. Each end of rod (2cm dia. And 0.5m long) is connected to thermal boundaries at 4K and 300 K.

Stainless steel: assume constant \( k=3 \text{ W/mK} \) \( \rightarrow \) \( q=1\pi1e-4*296/0.5=0.568 \text{ W} \)

Copper: assume constant \( k=300 \text{ W/mK} \) \( \rightarrow \) \( q=1\pi1e-4*296/0.5=56.8 \text{ W} \)
Thermal conductivity is a function of material.

When one performs a thermal analysis in a large temperature range, non-linear analysis is essential using a FEM code.
Convection heat transfer

Heat transfer occurring due to the bulk motion of fluid (gas, liquid).

The transfer of energy between an object and its environment, due to fluid motion.

Pressure $< 10^{-4}$ torr: negligible effect

Radiation heat transfer

The transfer of energy to or from a body by means of the emission or absorption of electromagnetic radiation

Electromagnetic Spectrum
Energy radiated per unit time and per unit area by the ideal radiator is given by the Stefan-Boltzmann law:

\[ E_b = \sigma T^4 \]

where \( \sigma \) is the Stefan-Boltzmann constant, \( 5.669 \times 10^{-8} \) W/(m\(^2\)·K\(^4\))

Ex.) Heat exchange between non-blackbodies

1) Two infinitely parallel plates\( \rightarrow \) \( \frac{q}{A} = \frac{\sigma(T_1^4 - T_2^4)}{1/\varepsilon_1 + 1/\varepsilon_2 - 1} \)

2) Two long concentric cylinders\( \rightarrow \) \( q = \frac{\sigma A_1(T_1^4 - T_2^4)}{1/\varepsilon_1 + (A_1/A_2)(1/\varepsilon_2 - 1)} \)

Inner cylinder: \( T_1, A_1, \varepsilon_1 \)
Outer cylinder: \( T_2, A_2, \varepsilon_2 \)

3) layers of low emissivity material and insulators.
   Ideally \( (q/A)_{\text{with shields}} = (q/A)_{\text{without shield}}/(1+n), \) \( n=\text{number of layers} \)
Phase diagram of $^4$He

Superfluid:
A phase of matter in which viscosity of a fluid vanishes.
Discovered in 1937 by Kapitza, Allen, and Misener.
L. Landau won the Novel Prize in Physics ‘phenomenological and semi-microscopic theory of superfluidity of $^4$He’.

Film creeping

Thermo-caloric effect
Cryogenic efficiency

Ideal Carnot efficiency

\[ \eta_{\text{ideal}} = \frac{T_{\text{op}}}{T_{\text{ambient}} - T_{\text{op}}} \]

Ex. Ideal case: \( \eta_{\text{ideal}}=0.345 \) for 300K \( \rightarrow \) 77K,
\( \eta_{\text{ideal}}=0.014 \) for 300K \( \rightarrow \) 4.2K

In practice, actual efficiency is much lower than this ideal case.
\( \eta/\eta_{\text{ideal}}=\eta_{\text{ratio}} \) typically ranges 0.1~0.35 (<0.1 in small systems)
Smaller machine has lower efficiency.
As technologies improve, efficiencies are getting higher.

Some reference numbers for scaling
Room temperature power/power at 4.5 K: 250~350
Room temperature power/power at 2 K: 1100~1300

Rough scaling:
If we have 100 W load at 2 K \( \rightarrow \) we need \(~120\) kW cryogenic system at least.
(we will re-visit this concern for machine efficiency estimation in Chapter 7)
Low efficiency + small heat capacity + expensive: need very careful design
Ex. SNS Refrigerator System

Helium Refrigerator System
2400 Watt Capacity@ 2.1Kelvin and
8300 Watt Shield Load @ 38/50Kelvin
15g/s Liquefaction at 4.5Kelvin
80g/s Liquefaction Mode

Cryogenic Transfer Line System
4.5K & 38K Helium Supply and
4.0K & 50K Helium Return

Whole system consumes >3 MW electricity
Schematics of cryomodule

- Helium supply line
- Helium return/pumping port
- Multi-layer insulator
- Helium vessel
- Thermal shield
- Magnetic Field shield
- Beam pipe
- Mechanical tuner
- Vacuum chamber
- RF power coupler
Cavity with Helium vessel

Cavity string

Space frame and thermal shield
Ex: SNS Cryomodule

End can for Helium supply

Magnetic field Shield

Thermal shield and Space frame

Vacuum Chamber

Power couplers and waveguide transitions

Helium vessel

End can for Helium return
Ex. SNS Cavity Assembly

- Medium Beta Cavity
- NbTi Dished Head
- Field Probe
- HOM Coupler
- Titanium Bellows
- Stiffening Rings
- 2 - Phase Return Header
- NbTi Dished Head
- HOM Coupler
- Fundamental Power Coupler
Comparisons of various modes of helium heat transfer

- **Downward:**
  - helium
  - metal

- **Upward:**
  - metal
  - helium
Resonance frequency control

**Slow tuner (mechanical tuner):**

Compensate static or quasi-static detuning 
(initial offset or slow drift of resonance frequency)

Compress/expand cavity length typically using stepper motor

Coarse tuning: usually put the resonance frequency in the allowable band

Typical tuning range: about +/- few mm

Types:
CEA/Scalay tuners
blade tuner (DESY, INFN)
side jack tuner (KEK)
Slow Tuner

Helium Vessel

Fast Tuner

Flexure Connection to Helium Vessel (2X)

Motor & Harmonic Drive

Piezo Actuator

SNS tuner (saclay-TTF generation I type)

INFN, Blade tuner for ILC

Side Jack tuner (KEK)
Fast tuner:

Fine & fast tuning

Pulsed operation: Compensate Lorentz force detuning within RF pulses

High $Q_{\text{ext}}$: Compensate microphonics

Piezoelectric actuators: electromechanical actuator. Linear electromechanical interaction between the mechanical and the electrical state in piezoelectric materials. Typical tuning range: few to several $\mu$m

Magnetostrictive actuator: solid state magnetic actuator. A current driven coil surrounding the magnetostrictive rod generates the expansion of the rod.
Piezoelectric actuator

Voltage is applied to the piezoelectric actuator device which make the piezo stack shrink/expand

Typically
Stroke: 70~80 mm for 100 mm stack at room temperature
stroke at cryogenic temperature → 5~10 % of that at room temperature
Resolution: ~Hz
Model vs. Reality

1. On the CAD Model

2.

3. Reality – Pretty Complicated
Power Coupler

Function: Deliver RF power
Coupling $\rightarrow Q_{ex}$

Concerns: Transmission loss
Thermal stability
Mechanical stability
Simplicity
Reliability
Cost
Multipacting

Frequency
Power needed
Coupling
Types
Cooling
Window
Coaxial

SNS power coupler

Waveguide

TTF3 coupler (ILC)
Multipacting simulations around ceramic window
Coupler conditioning